Thermal Dispersion Airflow Measurement

October 14, 2003

Energy Efficiency and Demand Analysis Division
**California Energy Commission**
1516 - 9th Street, MS-28
Sacramento, CA 95814

Attn. Mr. Brian Alcorn:

Re: Building Energy Efficiency Standards, Title 24 and $CO_2$-based Demand Control Ventilation

Subject: Issues concerning the difficulties in applying DCV with $CO_2$ sensors

Dear Mr. Alcorn:

Having only recently found and downloaded Ms. Peggy Jenkins' letter from the Indoor Exposure Assessment Section or the Air Resources Board of December 20, 2002, I would like to express my support of her conclusions and the proposal by Dr. Chris Federspiel of 11/5/01 for the 2005 Title 24 energy standards.

In anticipation of the 2005 review cycle, I would also like to highlight some technical reasons why $CO_2$-based Demand Control Ventilation is not reliable for ventilation control, nor the energy-conserving methodology that is being represented. It seems that it is only when $CO_2$ is compared to extremely energy inefficient system designs that this method provides calculated savings. This includes published examples using CAV and VAV with reheat, outside of the currently allowable system designs under the latest energy codes. There are significant risks of allowing intakes to close completely and thereby achieve reductions in energy consumption. There are also pressurization control implications that are not considered and that will conflict with strategies that use $CO_2$ for ventilation control exclusively.

$CO_2$-based Demand Control Ventilation schemes should be limited to those which directly verify intake rates as $CO_2$ levels or differentials attempt to reset those rates due to changes in occupancy. This will allow the system to minimize intake air conditioning and limit it only to that which is required by Title 24 for a given structure type, while simultaneously insuring that: intake rates never fall below design minimums, never exceed design expected maximums and that the intakes never close during occupancy. All of these conditions can and have occurred with $CO_2$-based direct ventilation control methods.

Our company has been involved with research and product development in the area of Outside Air Intake control since 1983. We have a significant amount of experience (almost 20 years) in providing instrumentation capable of accurately and reliably measuring intake airflow rates. During that period our research has been published in the ASHRAE Journal and other industry publications including *www.automatedbuildings.com*. Our findings 13 years ago on fixed-position intake damper control in VAV systems has been verified by ASHRAE Research Project RP-980 at the University of Colorado at Boulder (2000), and reflected in conclusions of ASHRAE Standards Committee 62.1 in Addendum "u" and section 5.3 of Standard 62-2001 for systems and equipment used to achieve required ventilation rates.

We currently have product being installed as the reference input for airflow control in the 5-building Advanced Measurement Lab Complex for NIST in Gaithersburg. We have had equipment in use at USACE-CERL, MIT, CalTech, CoU-Boulder, Penn State, Iowa Energy Center, Battelle (PNNL), Argonne National Labs et. al. for many years.

The current position of the Commission has been to either require or support the use of $CO_2$ – DCV. This position can actually backfire when the method referenced over-ventilates due to the errors experienced in $CO_2$ application, measurement, sensing or calculation.

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As a result of the nature of the measurement products we manufacture, we find ourselves helping many in the engineering community with new designs and fixing existing mechanical systems that have attempted to employ $CO_2$-based DCV. Our position on DCV is not contrary to minimizing energy usage, but we do embrace the concept of doing so without negatively impacting IAQ and occupant productivity and health. To accomplish this, a more precise control method is needed and direct measurement is far superior to all possible indirect methods of determining intake rates, especially under variable loads and variable internal and external conditions. These are the most compelling reasons to use direct feedback intake controls, particularly on all VAV designs and most multi-fan CAV systems.

A potentially greater problem is the energy usage, health impacts and costly building damage that will result from inadequate building pressurization control. Tracking return airflow rates to zone/space supply is a method that is much more reliable and more stable than direct static pressure control. The ultimate way of controlling space pressurization and a key component in maximizing energy usage during mechanical cooling mode is to measure "pressurization flow" directly and using it to reset a more stable equivalent - volumetric differential airflow. In other areas of the country, where heating is the larger energy component, pressurization flow should be maintained as close to net neutral as possible, to avoid forcing internal moisture into wall cavities where it can condense. This requires instrumentation that can measure and maintain as close to Zero differential pressures as possible. This level of performance is below the reliability threshold and temperature limitations of most commercially available static pressure devices.

As an indicator of occupancy, $CO_2$ can very useful to "reset" intake rates, as determined by some means of direct measurement. But, as a direct input for ventilation control, $CO_2$-based DCV contains too many questionable assumptions, which can make a bad situation worse. In the normal course of our business, we have often proposed the use of $CO_2$ for optimization in variable occupancy spaces, but have avoided the shortcomings of the method by coupling it with direct intake air measurement. $CO_2$ would then be used to modulate the intake damper to achieve rates between these bracketed limits achieved by direct control. We thereby avoid the tendency for $CO_2$ to over-ventilate or to completely close the intake dampers. We can maintain a minimum ventilation rate for building generated contaminants and have a positive limit on the total intake rate that the system will provide under mechanical cooling or heating. Direct intake control also gets us a step closer to energy efficient means of building pressurization control.

Although lengthy, there are a significant number of issues that need to be addressed and can be summarized for non-technical readers. A summary of the technical issues involved is attached and includes examples.

I hope we are able to broaden your knowledge and that of others at CAEC regarding the limitations of $CO_2$ measurement and its usage for control of ventilation rates. We also hope you recognize that the continual references in Title 24 allowing $CO_2$ for direct ventilation control may, in fact, expend much more energy than is assumed. We would be happy to provide a more formal presentation or one in person, such as those you have allowed which support $CO_2$-based Demand Control Ventilation.

Please let us know if we can answer any questions, schedule a presentation or can be of further assistance.

Sincerely,

***EBTRON, Inc.***

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# Limitations of Using $CO_2$ Inputs for Demand Controlled Ventilation

Both of the primary methods of using $CO_2$ for demand control are described and analyzed below. The single measurement of interior $CO_2$ levels has been routinely found not to be useful for ventilation control and no use in determining interior occupancy without exterior $CO_2$ measurement input. The two primary methods used are "concentration balance" and "mass balance". A third method of ventilation measurement using $CO_2$ is described in the ASTM Standard - D 6245-98, but due to its nature, it is not readily applicable to active control.

The following is an evaluation of the "concentration balance" technique, as it was described in ASHRAE Research Project RP-980 ***Error Analysis of Measurement and Control Techniques of Outside Air Intake Rates in VAV Systems,*** conducted at UC-Boulder, Department of Civil, Environmental, and Architectural Engineering. We quote…..

## $CO_2$ Concentration Balance

*Another indirect method for outside air intake rate measurement is using a concentration balance based on CO2 concentration levels. Numerous papers have been published dealing with this topic, including Drees et al. (1992), Elovitz (1995), Janu et al. (1995), Ke and Mumma (1997a), Ke et al. (1997b), Meckler (1994), and Persily (1993). In the CO2 concentration balance model, the outside air intake rate is based on a volume balance of the airstreams and is given by Equation 7. Similar to the enthalpy balance method, when the value of CO2RA – CO2OA becomes small, errors in the calculated outside air intake rate become very large (Janu et al. 1995).*

$$\dot{V}_{OA} = \dot{V}_{SA} \cdot \left( \frac{CO_{2RA} - CO_{2SA}}{CO_{2RA} - CO_{2OA}} \right) \qquad (7)$$

***where***
***$CO_{2OA}$ = outside air $CO_2$ concentration, ppm***
***$CO_{2RA}$ = recirculated air $CO_2$ concentration, ppm***
***$CO_{2SA}$ = supply air $CO_2$ concentration, ppm***

*The concentration balance airflow measurement technique expressed by Equation 7 is performed using one sensor to measure all three $CO_2$ concentration values. **Using multiple $CO_2$ sensors to determine the outside airflow rate is not possible due to the relatively large error associated with the absolute accuracy of commonly available sensors**. When only one sensor is used, however, the absolute errors cancel out of Equation 7. The only source of error associated with the sensor then becomes its repeatability. The use of only one sensor, however, increases the time required to calculate the outside airflow rate. Each airflow must be sampled by the sensor before the outside airflow rate can be calculated, and each airflow typically requires two to three minutes to be measured with reasonable accuracy. However, this **requirement for relatively stable $CO_2$ concentrations limits the applicability of the concentration balance technique.** In spaces where large, abrupt changes in occupancy (and, hence, $CO_2$ levels) can occur, this method may prove unreliable. This fact may rule out the use of this control strategy in spaces such as conference rooms and auditoriums or any building where large transient effects are possible……….*

*……….The predicted errors indicate that the concentration balance airflow measurement technique may be valid except when occupancy is low or when the difference in the recirculated and outside air $CO_2$ concentration levels is small. Additionally, when the outside air represents a small fraction of the total supply air provided, errors in the calculated outside airflow may become too large for reliable and accurate use.*

The preceding was extracted from *Error Analysis of Measurement and Control Techniques of Outside Air Intake Rates in VAV Systems, ASHRAE Transactions, 1999.*

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## $CO_2$ Mass Balance

The simple concept of the “Mass Balance” approach is so seductive, that everyone needs to understand the dangers involved in misusing the methodology or misapplying the principles.

First, examine the relationship between the mathematical components of the Mass Balance equation. The ANSI / ASHRAE Standard 62-1999 & 2001, provide us with the Mass Balance Equation in Appendix D. (below):

$$V_o = N / (C_s - C_o)$$

**Where,**

**$V_o$ = Outdoor air flow rate per person**
**N = $CO_2$ generation rate per person**
**$C_s$ = $CO_2$ concentration in the space**
**$C_o$ = $CO_2$ concentration in outdoor air**

The equation [Vo = N / (Cs - Co )] can be converted to volumetric units in CFM and concentrations in ppm. The revised equation becomes: Vo = 10,600 / (Cs - Co).

When applied to 1,000 ppm set point (700 ppm above a fixed outside base of 300 ppm); Vo = 10,593 / (1,000 – 300) = the familiar 15 CFM/person. If we calculate based on 800 ppm, the result is 21 cfm/person. Carrying this to an extreme, we can calculate for 600 ppm and get a required ventilation rate of 35 CFM/person. Remembering that the outside base was held constant at 300 ppm.

If we look at current actual $CO_2$ levels in cities, we find that an average closer to 400 ppm and was measured in numerous tests to range from 275 – 549 ppm (LBNL-43334, 1999). Readings above 500 are not unusual. Los Angeles and Mexico City have reported readings of 600 ppm or better. This puts a great burden on those who insist on controlling indoor $CO_2$ to a specific maximum level (and “assumed” static outdoor level), especially those that assume “if some is good, more is better”. For example, if we had an outdoor $CO_2$ level of 450 ppm and attempted to control ventilation to an indoor level of 600 ppm, we calculate that 70 CFM/person is required. Not very reasonable, is it?

A minority of authorities feel that increasing the amount of dilution ventilation based on a specific indoor $CO_2$ concentration may be assumed by some to be “linear and absolute”, when in fact it has been shown to be “inverse and relative”. ref. Feber, T.R., ASHRAE Journal. Lowering the internal level of $CO_2$ beyond a certain point does not necessarily provide the positive, energy saving results that are desired.

The following assumptions are required by the Mass Balance equation referenced in ASHRAE 62 to make calculated ventilation estimates useful:

1. **$CO_2$ measurements should be taken when the space reaches a “steady-state”.**
   Interior $CO_2$ concentrations should not fluctuate.
   Outside $CO_2$ concentrations are assumed to be constant in the calculation.
2. **$CO_2$ measurements are used in calculation without consideration of any measurement or sampling errors.**
   $CO_2$ sensors are assumed not to drift and do not require maintenance or recalibration over time, or between measurements.
3. **Human respiration is the same for all building occupants, regardless of: age, sex, size, diet, health, etc., or is a long-term average**
   Human activity is assumed the same for all building occupants.
   Human activity is assumed to equal that of a seated person.

The use of "averages" or time-equalized values undercuts the logic needed for the optimization of ventilation and energy usage in variable occupancy spaces.

The conditions described by these assumptions can only occur at a very specific single point-in-time. The inverse is also true – the assumptions cannot occur in a dynamic, fluid and changing environment. The very conditions when real "demand control" is most valuable.

It is assumed that $CO_2$ is measured with the use of a single, highly accurate instrument and that the calculations needed usually assume no measurement error. **Therefore, any of the possible $CO_2$ methods for the evaluation of ventilation effectiveness cannot be valid when applied to ventilation control in a dynamic building system, without making numerous and very questionable assumptions.** The question then becomes, are we really trying to ensure consistent intake rate control or just to provide for $CO_2$ limit control?

Here are extracts from a recent Lawrence Berkeley research report on $CO_2$ and ventilation control.

*According to equation (1) the ventilation rate can be estimated if the carbon dioxide source strength and the concentrations of supply air and room air are known (ventilation is the only significant process for carbon dioxide removal). Indoor and outdoor $CO_2$ concentrations are measured and the indoor $CO_2$ source strength is based on the number of occupants in a building and an estimate of their $CO_2$ production. However, this method is subject to several sources of error which are described in detail elsewhere (Persily 1997, Mudarri 1997, ASTM D 6245-98) and summarized below:*

- *Carbon dioxide concentrations have often not stabilized when the measurements are performed, and the use of non-steady-state values of carbon dioxide concentration in a steady-state mass balance equation usually leads to overestimation of the ventilation rate.*
- *Carbon dioxide concentrations are often measured using instruments, such as indicator tubes, with large potential errors.*
- *Concentrations of carbon dioxide in outdoor air vary with location and time, and significant error may result if assumed outdoor concentrations are used in calculations.*
- *The number, weight, activity and diet of the occupants affect the indoor carbon dioxide generation rate and each of these parameters can only be estimated.*
- *Indoor carbon dioxide concentrations may be spatially non-uniform and measurements at a few locations may not accurately represent the average concentration in the exhaust air.*
- *Use of the peak $CO_2$ instead of actual steady state values may produce erroneous ventilation rate estimates, off by a factor of 2 at low ventilation rates, and less at higher ventilation rates (Persily and Dols 1990).*

*The sampling strategy for $CO_2$ is extremely important. The indoor $CO_2$ concentration will generally be spatially non-uniform and measurement protocols should be designed to determine the average $CO_2$ concentration in the breathing zone or in the exhaust air streams. Precautions are necessary to avoid measurements in air directly exhaled by building occupants. The $CO_2$ concentration is seldom at steady state in real buildings because of variations in occupancy and ventilation rates. If occupancy and ventilation rate are reasonably stable, the time required to reach steady state depends on the ventilation time constant which is the reciprocal of the air exchange rate of the space; e.g., if the air exchange rate is 0.5 h-1 the time constant is 2 hours. A period of three time constants with a stable occupancy and ventilation rate is required for $CO_2$ concentrations to reach 95% of their steady state value. Three time constants corresponds to 6 hours if the air exchange rate is 0.5 h-1 and to 3 hours if the air exchange rate is 1 h-1.*

*Only two studies reported $CO_2$ as the differences between indoor and outdoor $CO_2$ concentrations, a more reliable indicator of the ventilation rate than indoor concentration. Outdoor air concentrations were reported only in six studies out of 22; these data showed a significant variation in outdoor air concentration (275 – 549 ppm). The large range of reported values are also likely to reflect measurement errors.*

*In addition to energy savings and improved health,* ***improved control of ventilation rates and other measures that improve indoor air quality in commercial buildings are a likely source of productivity gains.*** *The potential productivity gains from reduced respiratory illnesses and SBS symptoms have been discussed in detail by Fisk and Rosenfeld (1997, 1998) and Seppänen and Palonen (1998). The primary sources of productivity gains are reduced health care costs, reduced absence from work, and increases in the performance of workers while at work.*

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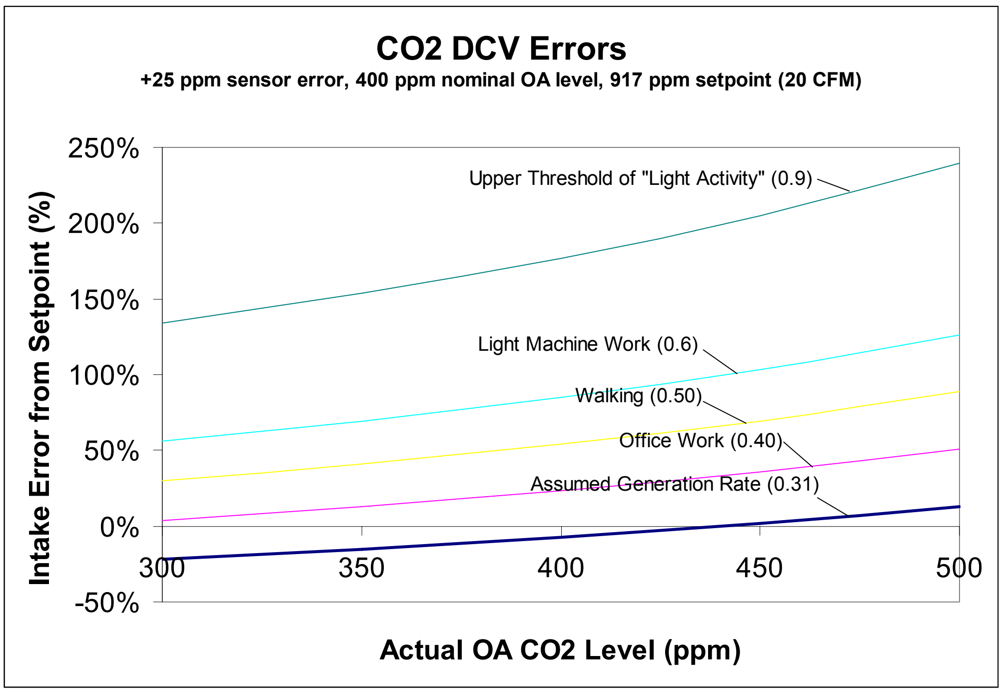
*These costs and the financial values of the reduced absences and performance increases are of the same magnitude as the total energy cost of the buildings, much larger than the costs of energy for ventilation (Seppänen and Palonen 1998, Seppänen 1999)*

The preceding extracts were taken directly from "Association of ventilation rates and $CO_2$ -concentrations with health and other responses in commercial and institutional buildings" presented and published in *Indoor Air 1999; 9: 226-252,* LBNL-43334.

If we pursue the logical conclusions from the warnings expressed by the research on $CO_2$, then: **variable occupancy spaces, which can most benefit from DCV, will perpetually be controlled to erroneously calculated intake rates because the theoretical "steady state" for the calculated relationships, can never be obtained in reality.** Depending on the combination of other sources of error in the assumptions, an increase above the assumed activity level together with a small error in OA carbon dioxide level, will normally produce a large positive error at the intake. The combination of these factors has been calculated and plotted below.

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Most of the technical references used in this letter are listed below for your convenience. Those in BOLD are more specific to our subject matter.

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